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ON THE DISPLACEMENTS OF THE TRIPLET BANDS NEAR λ3883 IN THE SOLAR SPECTRUM.

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In Kodaikanal Observatory Bulletin No. 39 some measures are given of the displacements at the centre of the Sun's disc of eight of the triplet bands between 3876 and 3882 The mean value of these and of three separate lines attributed by Rowland to carbon was + 0·0045 A, according to measures by the writer. If to this is added the value, + 0·002 A, found by Adams for the shift limb — centre for these bands the total shift limb — arc amounts to + 0·0065 A, a value approximating to the shift predicted by Einstein which for this region of the spectrum is + 0·0082 A.

More recent measures of these bands by St. John* indicated very much smaller shifts, the mean being +0·0018 A, at the centre of the disc, or less than one half the value obtained at Kodaikanal. St. John also measured 43 single lines of the carbon arc spectrum in the same region including 18 lines of intensities ranging from 2 to 4 and 25 lines of intensities between 00 and 1 of Rowland's Preliminary Table. These gave large individual differences, the shifts of the stronger lines, Sun — arc, ranging from + 0·006 A to — 0·003 A, and the weaker lines from + 0·004 A to — 0·003 A. The mean value for the stronger lines was + 0·0024 A, and for the weaker lines + 0·0006 A. At the Sun's limb his measures of 18 of the same series of stronger lines gave a mean value + 0·0037 A, whilst his means for 17 lines of the fainter series was zero.

With a view to clearing up this discrepancy between the Kodaikanal and Mount Wilson measures a new series of photographs was secured at Kodaikanal in March and April 1918. These were obtained with the large spectrograph described in Kodaikanal Observatory Bulletin No. 36, using the Anderson 6-inch grating with a ruling of 75,000 lines. Fourth order spectra were photographed at the centre of the disc, but most of the limb spectra were taken in the third order. The linear dispersion is 0·48 A per millimeter in the fourth order and 0·79 A per millimeter in the third order. The definition in both orders is very fine, and there is no trace of astigmatism. The band 3880·53 is partially resolved in the arc spectra of the fourth order, the triplets on the more refrangible side of this being clearly resolved.

Great care was taken to obtain plates only in the clearest possible sky when no trace of scattered white light was visible near the Sun ; in all cases also the altitude of the Sun exceeded 60°. The wave lengths of lines which are shifted towards red at the limb are reduced by scattered light, which superposes light from the centre of the disc, and this is especially liable to occur in the ultra-violet region where the scattering is greater than in the visible region.

The usual reflecting device was used for simultaneous exposures on Sun and arc, care being taken to insure the complete illumination of the grating by light from both sources. The slit width was between 0·010 mm. and 0·015 mm. with a collimator lens of 7′ 6″ focus.

In photographing the polar limb spectra the time was computed beforehand and for each day when the vertical diameter of the Sun's image projected by the siderostat coincided with the solar axis. This is easily

* Astrophysical Journal 46, 263

done and without any chance of mistakes by means of the tables constructed for the specroheliograph work. Photographs were then made of the North and South polar limbs alternately as near to the computed time as practicable. For the fourth order plates exposures of 2 minutes on Sun and 3 minutes on arc were found sufficient at the centre of the disc, and for the limb spectra in the third order the exposures were about 5 minutes on the Sun and 1 minute on the arc.

The Sun's image enlarged to a diameter of 80 millimeters was projected on to an engraved plate placed in front of the spectrograph slit. A hole in the plate 1 mm. in diameter and 1 mm. inside the limb admitted light to the slit. This hole was also the centre of a circle of 40 mm. radius upon which the image could be centred when photographing the centre of the disc.

The limb spectra represent points on the Sun 1/40 of the radius within the limb, the exact heliographic co-ordinates of which may be computed, using the middle time of exposure to determine the position angle of the slit on the Sun's disc As they were mostly taken very near to the north or south polar limbs the corrections for the solar rotation are very small or zero, but in all cases where the point photographed was at an appreciable distance from the Sun's axis the component in the line of sight of the solar synodic rotation was computed by the formula $V = [1{\cdot}507 \cos \phi + 0{\cdot}546 \cos^3 \phi - C] \sin \lambda \cos D$.* The velocity thus obtained was added algebraically to the velocities due to the Earth's orbital and diurnal movements and the resultant velocity expressed in angstroms applied to correct the measured displacements.

The Earth's orbital motion in the direction of the Sun is determined from the daily values of the radius vector given in the Nautical Almanac and the component of the diurnal motion from the formula Velocity in Km/sec $= 0{\cdot}464 \cos \phi \cos \delta \sin T$.

The proper selection of lines or bands which may be supposed to be unaffected by the presence of superposed lines of other substances is not very easy. After a careful comparison of the arc and solar lines I originally selected the thirty lines or bands given in the following list, taken from Rowland's table of solar lines.

λ	Origin	Intensity.	λ	Origin.	Intensity.
3819·197	C	1 Nd ?			
3819·346	C	1	3876·556	C	0
·412	C	1	·622	C	0
3822·406	C	0	3877·587	C	0
·470	C	0	·646	C	0
3830·745	C	0	3879·331	C	0
·801	C	0	·394	C	0
3831·174	C—	3d	·458	C	0
3835·298	C	0	3879 716	C	1
·342	C	0	796	C	0
3836·639	C	1	·851	C	0
689	C	1	3880 105	C	1
3844 378	C	4d ?	175	C	0
3845·149	C	1	·235	C	0
3846·777	C	1	3880 465	C	1
814	C	1	·532	C	2
3851·427	C	2 Nd ?	596	C	1
3852·541	C ?	2 Nd ?	3880 815	C	1
3858·822	C	2 N	·931	C	1
3862·627	C ?	2	3881·140	C	1
3863·533	C	3 N	·254	C	1
3864 438	C	3	3881 445	C	2
3865 282	C ?	3	543	C	1
3868·873	C	1	3881·729	C	1
·941	C	0	825	C	1
3869 179	C	0			
·305	C	1			
3872·312	C	0			

* Kodaikanal Observatory Bulletin No. 49.

In making up this list I was guided mainly by the agreement in relative intensity between the lines in the carbon arc and the corresponding lines in the Sun as judged by superposing the arc images on the absorption lines in the solar spectrum and observing the 'fit' of the lines and bands when the arc spectrum has been made a suitable density. Many of the lines measured by St. John were rejected because of the want of agreement in relative intensities or, in the case of the fainter lines measured by him because of the inherent difficulty of measurement especially in the limb spectra. The list includes all of those given in St. John's table 1 B, consisting of his stronger lines and partially resolved triplets, excepting the following —

λ	Reason for exclusion
3846·13 } 3853·62 }	Relatively too strong in Sun
3856·80	Difficult to measure satisfactorily
3866·12	Diffused towards violet in Sun

I also exclude the lines 3876·448 and 3877·481 giving a shift towards violet at the centre of the disc, because they are relatively too strong in the Sun.

My plates are somewhat underexposed towards the more refrangible end, and this is an added reason for confining attention to the less refrangible bands and stronger lines.

A preliminary set of measures of some of the plates was made by the late Mr. R. J. Pocock, whose mean results Sun — arc may be briefly summarised as follows :—

North limb plates	+ 0·004 A
South limb plates	+ 0·008 A
Centre of Disc	+ 0·004 A

In a detailed comparison of his measures with those of St. John we found that there was a general agreement in the case of St. John's direct measures of Sun — arc, and for the lines in his table 1 B, but larger values were found for the triplet bands near 3883 which were more nearly in agreement with the original Kodaikanal measures quoted at the beginning of this paper.

In the measures now to be recorded I have practically confined attention to the triplet bands in the first head, for which Pocock's results differed from St. John. This series gives fairly accordant values of the displacement at the Sun's limb, but as in all Sun — arc measures the mean result of all the lines or bands on plates taken on different dates show discordances largely in excess of the probable error of measurement. It is desirable therefore to reduce to a minimum the time spent on any one plate.

Two methods of measurement have been adopted. The limb spectra have all been measured by the ordinary method of bisection with a single thread made approximately parallel to the spectrum lines by tangent screw adjustment. The centre of disc plates, in which the triplet bands are partially resolved in the Sun, were measured by the negative on negative method, which can be used with great effect when suitable duplicate negatives have been secured. In this two similar negatives A and B are placed film to film in the positive on negative micrometer, but are not reversed end for end. They are displaced laterally, so that the arc lines of A are superposed on the solar lines of B, and *vice versa*. The movement required to produce alternate coincidences measures the double displacement of the solar lines with reference to the arc lines. This method is especially suitable for measuring the stronger unresolved, or partly resolved, bands, but not for faint single lines. As in the positive on negative method used for other Sun — arc spectra, and for solar rotation spectra, the negative on negative measures are found to give slightly smaller values of the displacements than the bisection method.* This I consider may be due to an unconscious systematic overestimate of a small displacement when measuring by the ordinary method. It is not known how the discordance may vary with the amount of the displacement, but the effect on a measured displacement of 0·015 mm. is about 16 per cent, and in the present series of measures where the correction for motion is subtractive the difference between ordinary and negative on negative measures in the residual shift amounts to about 20 per cent. If we consider the

* Kodaikanal Observatory Bulletin No. 32.

negative on negative method to be more trustworthy an approximate correction may be applied to the measures made by the ordinary method, corresponding to a reduction of the shift by about one-fifth of its amount.

Results for the centre of the Sun's disc.—I now give in table I on page 303 the results of the measures of twelve centre of disc plates measured in six pairs by the negative on negative method. The mean shift Sun — arc for each of the bands is given in the last column, and the mean shift for all the bands in each pair of plates at the foot of the columns. The general mean is very nearly + 0·004 A if the anomalous result for April 6 is omitted or + 0·003 A if it is included.

The means for the individual bands, excepting one, vary from + 0·002 A to + 0·005 A. The exception, 3879·79, giving a zero shift needs further study. In our previous measures and in those of St. John the less refrangible portion of this band has a shift of + 0·003 A, and the difference may be due to the fact that in the negative on negative measures the entire triplet is measured as one line, whereas in the bisection measures the more refrangible single line 3879·716 of Rowland was omitted. This line (Series A_1 of Uhler and Patterson) may give a negative shift, as appears to be the case also with the lines of the same series at 3877·481 and 3876·448. These two lines were omitted from the present measures because their intensities and their positions relative to the doublets of the A_2 series differ markedly in Sun and arc. This is clearly shown by comparing the intensities and wave-lengths in Rowland's "Preliminary Table" with the table of carbon arc wave-lengths of Uhler and Patterson*; the intensity of each is relatively too great in the Sun and they are displaced towards violet 0·011 A and 0·008 A respectively. It seems most probable that these lines are blended with lines of other elements, otherwise it has to be supposed that under solar conditions there is some special perturbation affecting the wave-lengths and intensities of these particular lines of the A_1 series, including possibly the line 3879·716, but not other lines in the same series.

The more refrangible component of the triplet at 3879·39 appears to be blended with another line on its red side but this can have little or no effect on the position of the band as a whole.

The mean shifts for all the bands show a fair accordance on the different dates excepting April 6 which yields a zero result. This is not due to imperfect centring of the Sun's image on the slit, for a maladjustment amounting to about 6 mm. towards the east side would be required to neutralise by the solar rotation the mean shift towards red of 0·0037 A given by the other plates. Our long series of measures of Sun — Fe arc often have shown similar anomalies, due probably to local ascending currents at the centre of the disc; and we have recently proved that the spectrum lines may be locally displaced by small amounts at the centre as well as in other parts of the disc.

Measures by the negative on negative method have also been made of nine lines in the more refrangible region. The mean results for eight plates, including the pair of April 6 giving low values is as follows:—

λ	Origin.	Intensity.	Sun — arc in $\frac{A}{10,000}$.	Series (Uhler and Patterson)
3831·174	C—	3 d	+ 71	A_1
3836·639	C	1		
689	C	1	+ 59	A_1 B_1 C_1
3844·378	C	4 d ?	+ 37	A_1
3845·149	C	1	+ 37	B_1
3846·777	C	1		
·814	C	1	− 03	A_1
3851·427	C	2 N d ?	+ 43	A_1
3852·541	C	2 N d ?	+ 21	A_1
3868·873	C	1		
·941	C	0	− 03	B_1 B_2
3869·179	C	0		
·305	C—	1	+ 39	A_1

Mean + 0·0033

Mean excluding plates of April 6 + 0·0043.

* Astrophysical Journal 42, 439.

The close agreement here shown with the mean shift for the ten bands gives some confidence in the statement that for the stronger lines and bands in the carbon arc spectrum there is a shift towards red at the centre of the Sun's disc which is near to the value +0·004 A. This is a trifle smaller than the value previously found at Kodaikanal, but the earlier measures were made by the ordinary bisection method, which as already stated gives larger values.

Results for the Sun's limb.—In the limb spectra the eight triplet bands and two doublets at 3876·6 and 3877·6 are not resolved. Owing to the widening of all lines near the limb the components merge into one another and no spectrograph can resolve them.* I have found that the third order spectra with lower dispersion and greater contrast are more satisfactory to measure than the fourth order plates. The bands are of more uniform density than at the centre of the disc, and they can be easily measured as single lines by the bisection method. The negative on negative method would have been preferable, but suitable pairs of negatives were not available except in a few cases. The whole series was therefore measured by the bisection method.

Tables 2 and 3 (page 303) give the results of 6 north limb plates and 7 south limb plates. The displacements towards red are larger than was anticipated, the general mean being + 0·0071 A for the north limb and + ·0100 A for the south. There is a close agreement between the different bands, and 3879·79 which gave a zero shift at the centre here shows no anomaly.

The systematic difference between north and south is interesting, and confirms Mr. Pocock's measures. At first sight one might suspect that by some error of adjustment of the solar image an uncorrected rotation component of opposite sign in the two hemispheres affects the results. This is however very improbable, as the error in the estimate of the rotation component would need to be about 0·1 Km/sec., which would involve quite a large deviation of the slit from the position angle of the Sun's axis.

Corrections.—For the sake of completeness I give in tables 1 and 5 the data used for computing the rotation correction and the values of the orbital and diurnal movements of the Earth. In column 3 of these tables ϕ is the apparent latitude or position angle counted from the solar equator of the intersection of the spectrograph slit with the limb. ϕ' and λ are respectively the heliographic latitudes and longitudes of the points photographed. The following columns give the component in the line of sight of the Sun's rotation movement, of the Earth's orbital, and of the Earth's diurnal movement in Km/sec. Column 9 gives the residual motion or algebraic sum of the quantities in the three preceding columns; and in the last column this is expressed in angstroms and is the correction which has been applied to the measured displacements. This correction is in all cases subtractive because of the considerable motion of recession of the Earth from the Sun in April, involving a general shift of the solar lines towards red.

Summary of results.—If we make allowance for the difference between the bisection method of measurement and the more accurate negative on negative method the general means in the limb spectra should be reduced in the ratio 120 to 100. The results for all the spectra measured may therefore be stated as follows:—

	In angstroms.	In Km/sec.
North limb spectra	+ 0·0057	0·44
South limb spectra	+ 0·0080	0·62
Centre of disc	+ 0·0037	0·29

These are the mean shifts for the ten measurable bands in the first head between 3875 and 3883, and it is believed that they represent very approximately the displacements that would be observed were these bands in the Sun freed from all interfering lines of other substances.

It is not claimed that the results here given represent satisfactory mean values of the shifts, because the individual plates both of limb and centre show somewhat discordant values indicating the necessity for measuring a large number of plates preferably taken at different points on the solar limb, before a definite

* The band 3879·8 alone shows a rift due to a partial separation of the more refrangible line of the triplet.

conclusion can be reached. The systematic difference between north and south also points to a certain instability of wave-length in the solar lines

The result for the south limb plates is remarkably close to the shift corresponding to 0·634 Km/sec. predicted by Einstein and taken by themselves these results must be considered distinctly favourable to the relativity effect. The smaller shift at the centre of the disc is readily explained by an outward radial movement of the solar gases which might produce a partially compensating shift towards violet at the centre But Fowler has expressed the view that any rising movement on the Sun must be compensated by a downward motion, and that the descending gases would be more likely to produce absorption lines than the hotter ascending gases. Against this however we may argue that the gases which are in a state of the most extreme tenuity are in reality driven out from the Sun continuously into the coronal region by light pressure, as appears to be the case in the eruptive prominences, so that no downward compensating motion would be observed.

These results appear to be in serious disagreement with those of St. John who concluded that "within the limits of error there is no evidence of a displacement either at the centre or at the limb of the Sun of the order of 0·008 A as required by the principle of relativity" St John did not measure the displacement of the bands in the first head at the limb of the Sun, and his conclusion is largely based on the mean shift of 17 lines of small intensity which was zero. The question whether the carbon arc band lines (which are unaffected by pressure or pole effect in the arc) do or do not confirm Einstein's prediction resolves itself into the question whether we should place more reliance on the strongly marked triplet bands or on the single weak lines measured by St. John, and this again raises the question whether the strong and weak lines if freed from all interference by lines of other substances would actually be shifted by equal amounts

In the case of iron the shift of the lines at the centre of the disc or in general sunlight depends largely on intensity, the strong lines being much more shifted than the weak: but at the limb the shifts are approximately equalised, so that the great difference of shift between the stronger and weaker lines of the carbon arc at the limb is anomalous and needs further investigation.

I have pleasure in acknowledging the very material aid rendered in this research by First Assistant A. A. Narayana Ayyar, B.A. Most of the measures of limb spectra were made by him and he also performed all of the computations necessary for determining the corrections.

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TABLE I.—CENTRE OF DISC — ARC IN A/10,000.

Mean Wave length of band Rowland	1918 March 26d 11h 50m & 30d 9h 42m correction —40	1918 March 29d 11h 43m & 29d 11h 47m correction -54	1918 April 1d 10h 56m & 1d 11h 02m correction —44.	1918 April 2d 11h 25m & 2d 12h 01m correction —56.	1918 April 3d 9h 51m & 3d 9h 56m correction —23.	1918 April 6d 11h 01m & 6d 11h 06m correction —45.	Means.
3876·59 ...	+ 43	+ 46	+ 25	+ 26	...	0	+ 28
3877·62	+ 46	+ 34	+ 34	+ 16	.	− 04	+ 25
3879·39	+ 94	+ 68	+ 36	+ 19	+ 35	+ 09	+ 43
3879·79 ...	+ 24	+ 08	− 04	− 05	− 13	− 32	− 04
3880 17	+ 45	+ 17	+ 38	+ 27	+ 31	+ 12	+ 28
3880 53	+ 61	+ 53	+ 61	64	+ 51	+ 09	+ 50
3880·87 ...	+ 39	+ 53	+ 43	+ 28	+ 31	+ 02	+ 33
3881 20 . ..	+ 29	+ 06	+ 23	+ 22	+ 42	− 11	+ 18
3881·49	+ 51	+ 25	+ 57	+ 30	+ 49	+ 19	+ 38
3881 78 ..	+ 47	+ 49	+ 64	+ 37	+ 68	+ 15	+ 47
Means ...	+ 0·0048	+ 0·0036	+ 0·0038	+ 0·0026	+ 0 0037	+ 0·0002	+ 0·0031

General Mean omitting April 6 + 0·0037 A.

TABLE II.—NORTH LIMB — ARC IN A/10,000.

—	1918 April 6d 10h 13m correction -34	1918 April 9d 10h 19m correction —32.	1918 April 9d 10h 32m correction —26.	1918 April 10d 10h 24m correction —28.	1918 April 11d 10h 19m correction - 29.	1918 April 17d 10h 10m correction —30.	Means.
3876 59 ..	+ 47	+ 71	+ 59	+ 63	+ 115	+ 57	+ 69
3877·62 .. .	+ 99	+ 61	+ 61	+ 78	+ 69	+ 57	+ 71
3879·39	+ 67	+ 50	+ 117	+ 82	+ 116	+ 49	+ 80
3879 79 ..	+ 22	+ 68	+ 98	+ 113	+ 147	+ 53	+ 83
3880 17	+ 33	+ 66	+ 70	+ 105	+ 124	+ 76	+ 79
3880 53	+ 52	+ 64	+ 78	+ 78	+ 83	+ 35	+ 65
3880 87 . ..	+ 70	+ 33	+ 57	+ 59	+ 101	+ 70	+ 65
3881·20	+ 26	+ 25	+ 43	+ 36	+ 77	+ 43	+ 42
3881·49	+ 81	+ 82	+ 95	+ 89	+ 116	+ 115	+ 96
3881·78 .	+ 63	+ 44	+ 78	+ 66	+ 101	+ 34	+ 64
Means ..	+ 0·0056	+ 0 0056	+ 0 0076	+ 0·0077	+ 0·0105	+ 0 0059	+ 0·0071

TABLE III.—SOUTH LIMB — ARC IN A/10,000.

—	1918 April 6d 10h 04m correction —24	1918 April 9d 10h 12m correction —33.	1918 April 9d 10h 38m correction —54.	1918 April 10d 10h 17m correction —36.	1918 April 11d 10h 12m correction —32.	1918 April 16d 11h 41m correction —107.	1918 April 17d 10h 01m correction —21	Means.
3876·59 . .	+ 45	+ 112	+ 102	+ 143	+ 175	+ 105	+ 88	+ 110
3877·62 ..	+ 78	+ 128	+ 147	+ 115	+ 132	+ 83	+ 108	+ 113
3879·39 . .	+ 31	+ 89	+ 96	+ 126	+ 152	+ 91	+ 107	+ 99
3879·79 ..	+ 37	+ 57	+ 144	+ 128	+ 141	+ 83	+ 63	+ 93
3880·17	+ 21	+ 89	+ 101	+ 86	+ 155	+ 86	+ 81	+ 88
3880 53 ...	+ 76	+ 80	+ 121	+ 142	+ 232	+ 96	+ 57	+ 115
3880·87 ..	+ 105	+ 78	+ 94	+ 112	+ 119	+ 52	+ 112	+ 96
3881·20	+ 30	+ 69	+ 25	+ 74	+ 63	+ 115	+ 73	+ 64
3881·49	+ 87	+ 62	+ 119	+ 146	+ 187	+ 122	+ 88	+ 116
3881·78	+ 113	+ 64	+ 110	+ 118	+ 125	+ 113	+ 91	+ 105
Means ...	+ 0 0062	+ 0·0083	+ 0·0106	+ 0·0119	+ 0·0148	+ 0·0095	+ 0·0086	+ 0·0100

TABLE IV.—NORTH LIMB CORRECTIONS.

Date.	Hour	ϕ	ϕ'	λ	Rotation.	Orbital.	Diurnal.	Residual.	A
1918.	H. M.	°	°	°					
April 16 ...	10 13	89 8		.		+ 0 507	— 0 245	+ 0 262	— 0 0034
,, 9 .. .	10 19	89 1	70	2 E	— 0·017	+ 0·499	— 0 232	+ 0 250	— 0·0032
,, 9 . ..	10 32	86·2	70	11 E	— 0 090	+ 0 499	— 0 210	+ 0 199	— 0·0026
,, 10	10 24	87 8	70	7 E	— 0·058	+ 0·495	— 0 223	+ 0·214	— 0 0028
,, 11 .	10 19	88·2	70	5 E	— 0 041	+ 0 492	— 0 230	+ 0 221	— 0 0029
,, 17	10 10	89·6	..	...		+ 0 471	— 0·242	+ 0 229	— 0 0030

TABLE V.—SOUTH LIMB CORRECTIONS.

Date	Hour.	ϕ	ϕ'	λ	Rotation	Orbital.	Diurnal	Residual	A
1918.	H M.	°	°	°					
April 6	10 04	87·6	81	17 E	— 0 058	+ 0 507	— 0 259	+ 0 190	— 0 0024
,, 9	10 12	89 7	...	.		+ 0 499	— 0 244	+ 0 255	— 0·0033
,, 9	10 38	84·9	81	35 W	+ 0·115	+ 0 499	— 0 199	+ 0·415	— 0·0054
,, 10 ...	10 17	89 2	82	7 W	+ 0·021	+ 0 495	— 0·235	+ 0 281	— 0·0036
,, 11	10 12	90 0		..		+ 0·492	— 0·242	+ 0 250	— 0·0032
,, 16	11 41	71·8	70	65 W	+ 0·429	+ 0·473	— 0 076	+ 0·826	— 0·0107
,, 17	10 01	87·7	80	14 E	— 0 055	+ 0 471	— 0·257	+ 0 159	— 0 0021

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